The multiscale interactions in Atlantic Tropical cyclone genesis and intensification

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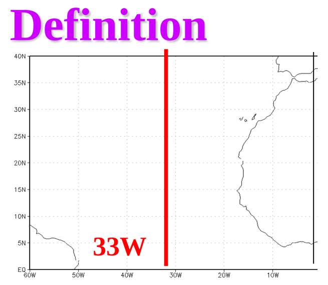
Introduction

Tropical cyclone (TC) development involves complicated multiscale interactions. In the past few decades, Atlantic TC track forecasts have been significantly improved; however, genesis and intensity forecasts still remain unsatisfactory. One of the reasons might be incomplete knowledge of the entire life cycle of TC activities. Therefore, it is very important to fully understand the dynamical and physical processes of both TC precursors and African easterly waves (AEWs) in order to improve TC forecasts. In this study, first we use various satellite data and the ECMWF Re-Analysis (ERA) Interim dataset to examine the influences of the Sahara air layer (SAL) and mesoscale vortices on early developing disturbances (EDDs) by examining cases within the past eleven years. Second, we assimilate observations into model simulations to generate high-resolution (4 km) reanalysis to study the seven waves that were investigated during the NAMMA field experiment. In addition to EDD, the discussion also includes late developing disturbances (LDDs) and non-developing disturbances (NDDs) and investigate the storm scale vortex and cloud interactions.

Definition



- EDD: Reached the intensity of a tropical depression (TD) at the east of 33W
- LDD: Reached TD intensity at the west of 33W
- NDD: Never reached TD intensity

Note: LDDs and NDDs are called NEDDs in analyzing ERA data.

Data

- Best track data from NHC.
- Globally-merged InfraRed (IR) brightness temperature data from GES DISC.
- Daily TRMM precipitation estimates (i.e., 3B42 product).
- Reanalysis data from ECMWF Re-Analysis (ERA) Interim dataset.
- Daily global aerosol optical depth (AOD) data from MODIS.
- NAMMA field experiment data

Data Pool in EC experiments

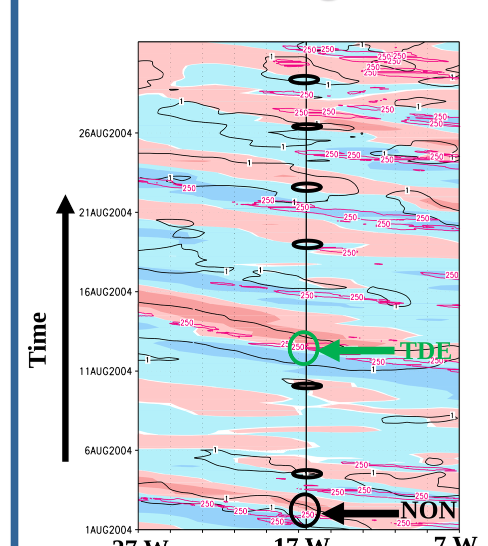
EDD (25 cases)

	Jun	Jul	Aug	Sep	Oct	Nov
2000	x	x	1	2	x	x
2001	x	x	x	1	x	x
2002	x	x	1	x	x	x
2003	x	x	1	1	x	x
2004	x	x	1	3	x	x
2005	x	x	x	x	x	x
2006	x	x	1	1	x	x
2007	x	x	1	1	x	x
2008	x	1	x	1	x	x
2009	x	x	2	1	x	x
2010	x	x	2	3	x	x

NEDD (33 cases)

	Jul	Aug	Sep
2000	x	0	2
2001	x	x	1
2002	x	0	x
2003	x	4	3
2004	x	1	2
2005	x	x	x
2006	x	3	2
2007	x	2	3
2008	3	x	3
2009	x	2	1
2010	x	0	1

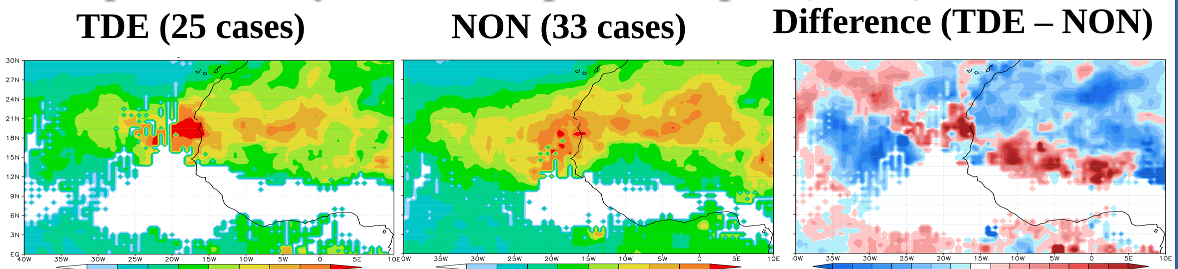
Hovmoller Diagrams



- **Shading: 700-hPa meridional winds averaged between 5° N - 15°N (m s^{-1}), EC interim dataset.**
- **Pink contours: Observed IR brightness temp averaged between 5° N - 15°N (K). The threshold is 250 °K.**
- **Black contours: 850-hPa relative vorticity averaged between 5° N - 15°N (10^{-5} s^{-1}), EC interim dataset.**

- EDDs and NEDDs possessing similar characteristics are selected in the same month.
- By doing this, we filter out non-essential samples to better identify significant and meaningful differences between cases.

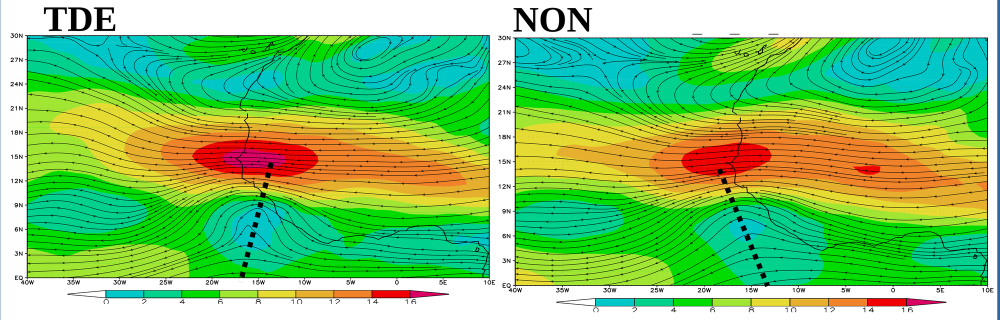
Composite Daily Aerosol Optical Depth (AOD)



Southward shift of dust induces:

- Increase of positive temperature gradient anomaly
- Increase of AEJ intensity via thermal wind balance
- Stronger ITCZ and heavier precipitation for TDE

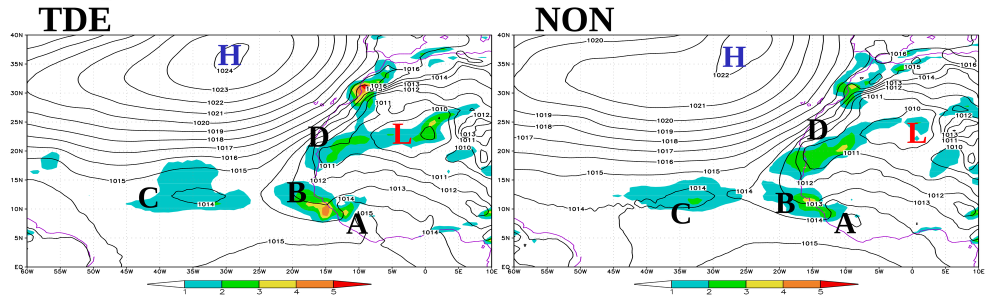
Composite 650 hPa Wind Speeds and Streamline



TDE:
- Stronger AEJ
- Diffluent trough titling upstream

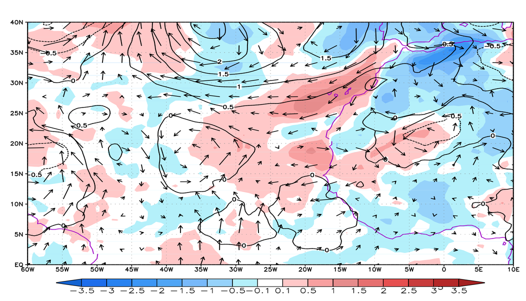
NON:
- Weaker AEJ
- Confluent trough tilting downstream

Composite 900 hPa Relative Vorticity & SLP



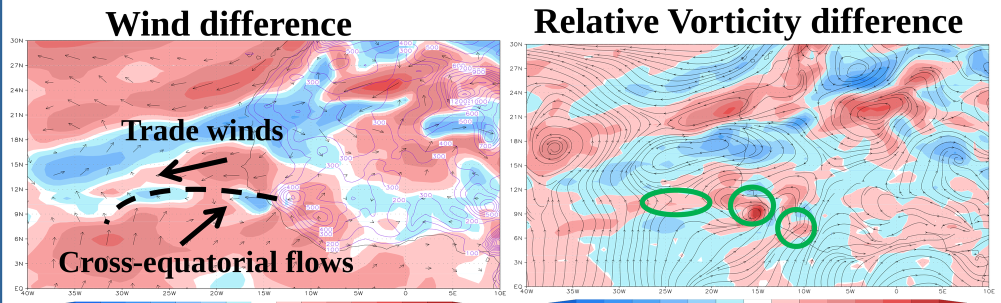
- Compared to NON, TDE has stronger high pressure system extending southeastward and stronger thermal low.
- A: southern local vorticity; B: current AEW's vorticity; C: previous AEW's or remnant vorticity in the convergent zone. D: northern vorticity strip.

Composite 950 hPa T & Winds & SLP Differences



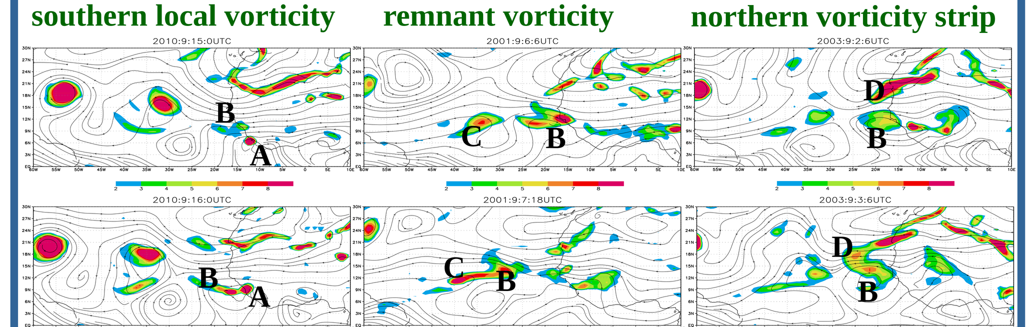
- The cyclonic circulation anomaly help SAL move southward.
- Shading: 950 temp anomaly
  Contour: SLP difference

Composite 900-hPa winds & vorticity differences



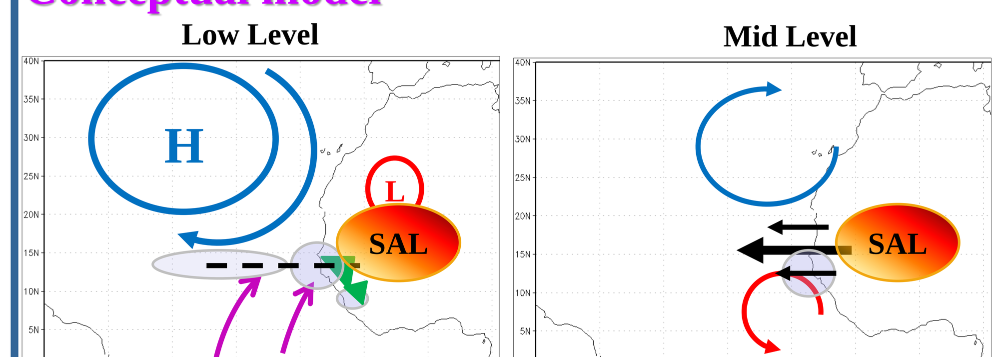
- Stronger high → increasing trade winds + stronger cross-equatorial flows → enhancing convergence zone → active ITCZ →stronger subsidence to the north + stronger cross-equatorial flow→ intensifying high (positive feedback among high, cross-equatorial flow, and ITCZ).
- Stronger convergence zone/ ITCZ → stronger vorticity

Three Vorticity Sources for Vorticity Merger

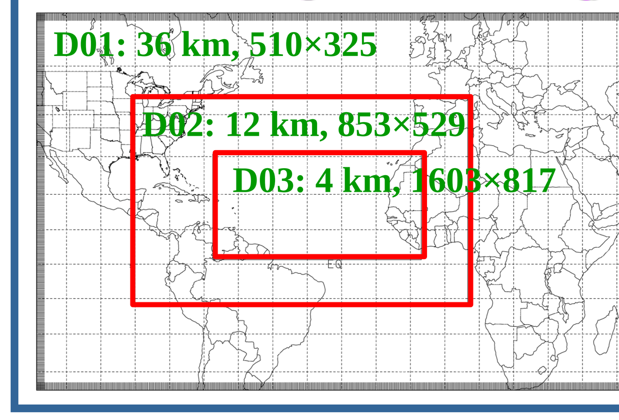


- 24 out of 25 cases in TDE has gone through mesoscale vortex merging opposed to only 11 out of 33 cases in NON.
- Energy accumulation inside the convergence zone and energy dispersion might also contribute to the formation of early developing waves.

Conceptual model



Numerical Experiment Design



Parameter setup:

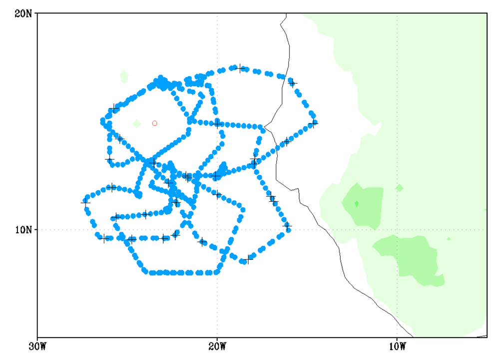
- WSM 6class microphysics
- Kain-Fritsch cumulus;
- RRTM long wave radiation
- Dudhia short wave radiation
- YSU PBL

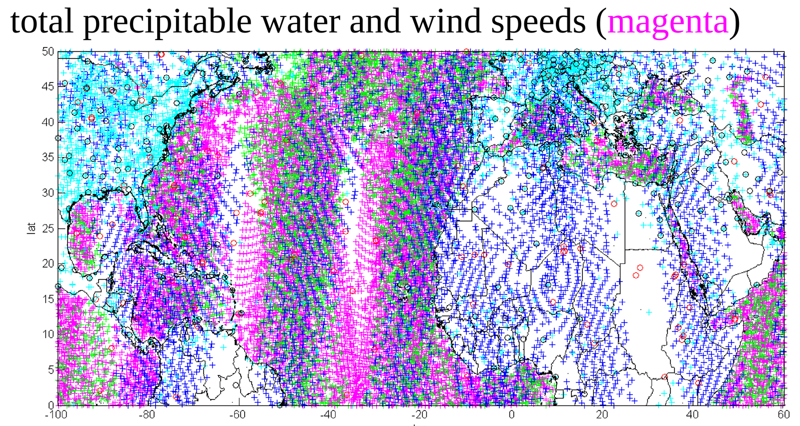
Data Assimilation

- **3-h update cycling through the entire simulation**

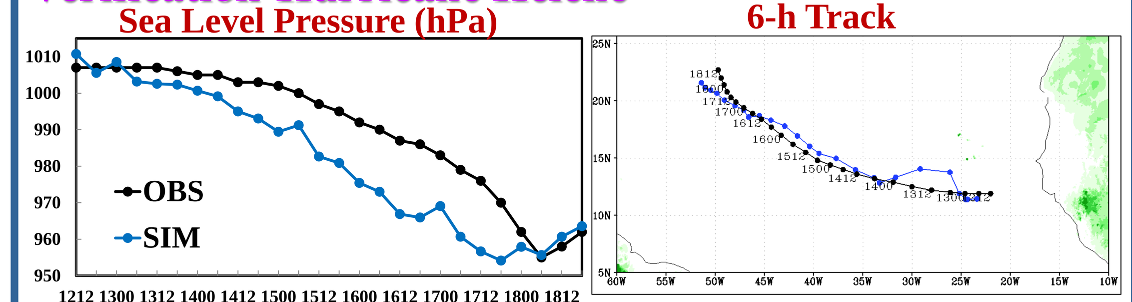
a) NAMMA experiment
- Dropsondes (black).
- MMS measurement (blue).
- Radiosondes (red).

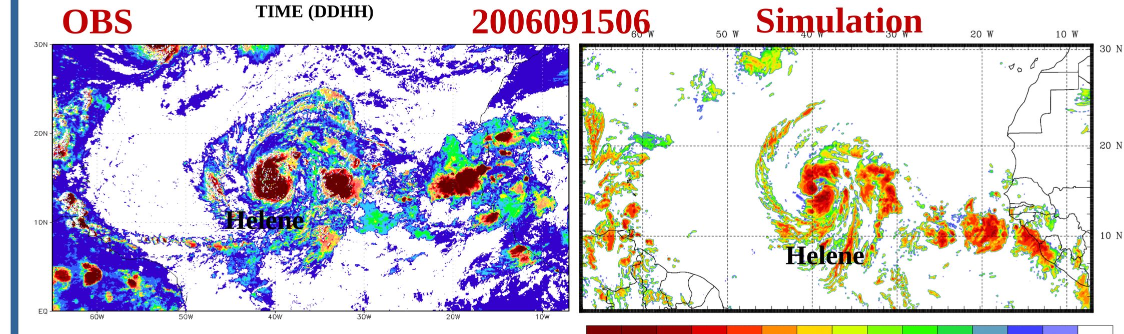
b) Convention data (cyan and black)
c) QuikSCAT wind vectors (green)
d) GPS refractivity (red).
e) AIRS temperature soundings (blue)
f) SSMI total precipitable water and wind speeds (magenta)



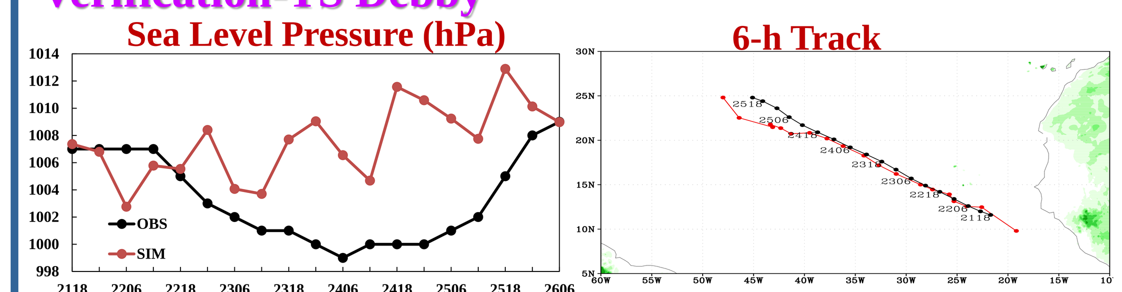


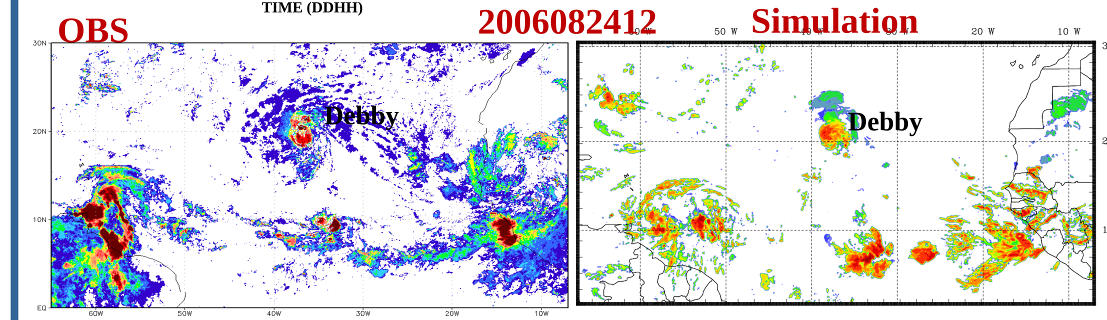
Verification-Hurricane Helene



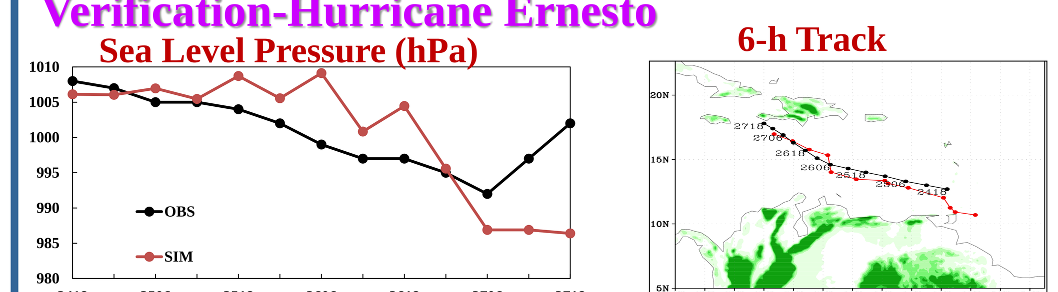


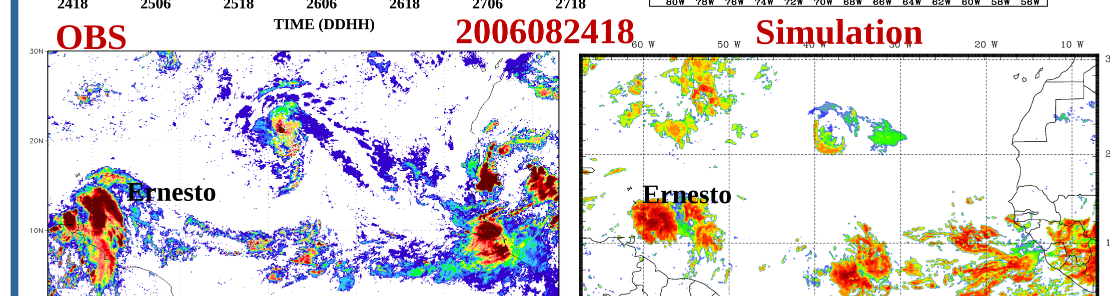
Verification-TS Debby





Verification-Hurricane Ernesto

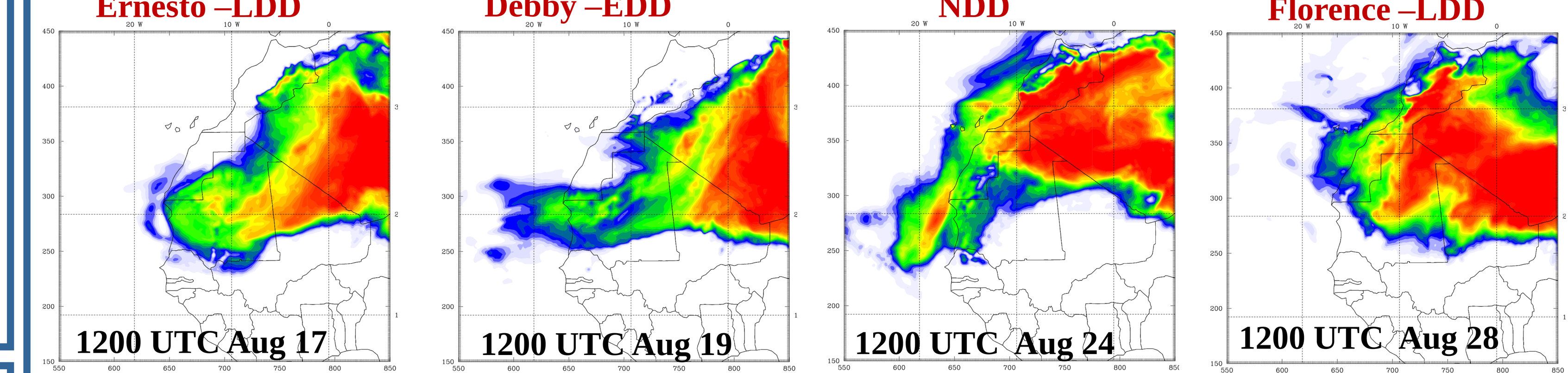


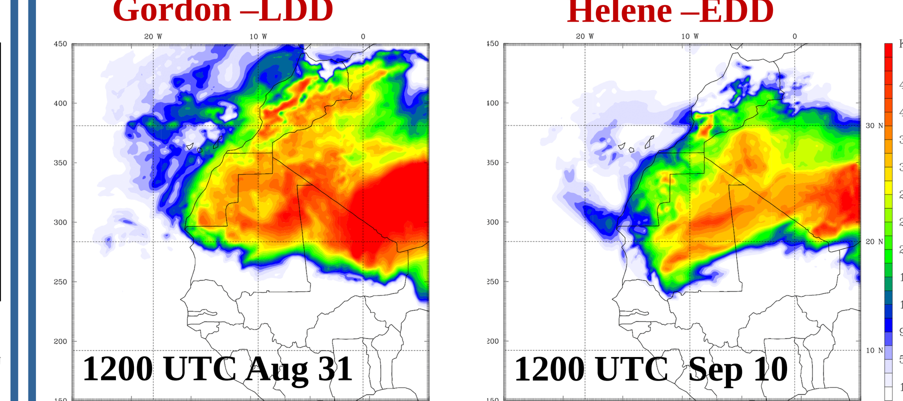


Seven waves during NAMMA experiment

Wave #	Time left West Africa	Developing period	Observed date	Name	Simulation period	Type
1	Aug. 18	1800 UTC Aug. 24 ~1200 UTC Sep. 01	Aug. 19, 20	Hurricane Ernesto	0000 UTC Aug. 14~ Aug.31	LDD
2	Aug. 20	1800 UTC Aug. 21~ 0600 UTC Aug. 26	Aug. 23	TS Debby	0000 UTC Aug. 14~ Aug.31	EDD
3	Aug. 25		Aug. 25, 26	Non-developing disturbance	0000 UTC Aug. 21 ~Sep. 2	NDD
4	Aug. 29	1800 UTC Sep. 3~ Sep. 12	Sep. 1	Hurricane Florence	0000 UTC Aug. 25 ~Sep. 20	LDD
5	Sep. 1	1800 UTC Sep. 10~ Sep. 20	Sep. 3, 4	Hurricane Gordon	0000 UTC Aug. 25 ~Sep. 20	LDD
6	Sep. 8		Sep. 8, 9	Non-developing disturbance	0000 UTC Aug. 25 ~Sep. 20	NDD
7	Sep. 11	1200 UTC Sep. 12~ Sep. 24	Sep. 12	Hurricane Helene	0000 UTC Sep. 7~Sep. 20	EDD

SAL parameter





- Southward intrusion of SAL occurred for Ernesto and Helene but not in other LDDs and NDDs.
- Debby did not have significant southward intrusion of SAL. This might explain why the simulated intensity of Debby was not strong enough.

$$SAL = (\theta - \bar{\theta}) \times RH_{depression}$$

Summary

EC experiment

1. In the analysis data pool, TDE and NON possessed similar characteristics (i.e., an AEW accompanied by an 850 hPa vorticity precursor and active convections) and occurred during the same month for years 2000 to 2010.
2. The composite results show that TDE has a southward intrusion of the SAL over the West African continent.

   At low levels:

   Southward intrusion of the SAL coincides with an intensifying high pressure system extended southeastward and a stronger thermal low over West Africa. The stronger high pressure system accompanies stronger trade winds and cross equatorial winds, resulting in a stronger and more concentrated confluence zone near ITCZ. The subsidence from the ITCZ would also enhances the high pressure system via positive feedback. The stronger and more concentrated confluence zone also increased low-level vorticity intensity. The stronger confluence zone and stronger vorticity provide a more favorable environment for genesis and mesoscale vortex merging, which consequently help the low-level vortex rapidly spin up. In addition, the cyclonic circulation anomaly associated with the stronger thermal low also help the SAL intrude southward.

   At midlevel:

   Due to the southward intrusion of SAL, TDE has a stronger AEJ via thermal wind balance. Stronger AEJ induces higher barotropic instability and stronger positive horizontal advection of relative vorticity to the south. In addition, TDE has diffluent trough titling downstream. This offers a favorable mid-level synoptic environment for surface cyclongensis and stronger mid-level vortex downward development. The stronger vortex at the south of the jet continues to intensify and develop downward and couples with the surface vortex, speeding up the development via the vortex stretching effect, and then becomes an early developing disturbance.

High Resolution experiment

1. The high resolution reanalysis data are generated using WRF and WRFDA assimilating NAMMA experiment data and other satellite data and successfully capture the genesis time and location, track, and mesoscale cloud systems. Three-hour update cycling data assimilation significantly improves the performance for long period simulations (i.e., LDDs).
2. Result shows that Helene (EDD) has southward intrusion of the SAL before it leaves the coast and other LDDs (Gordon and Florence) and NDDs do not. However, Debby (EDD) does not have significant southward intrusion of the SAL, which might explain why the simulated intensity is too weak.

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